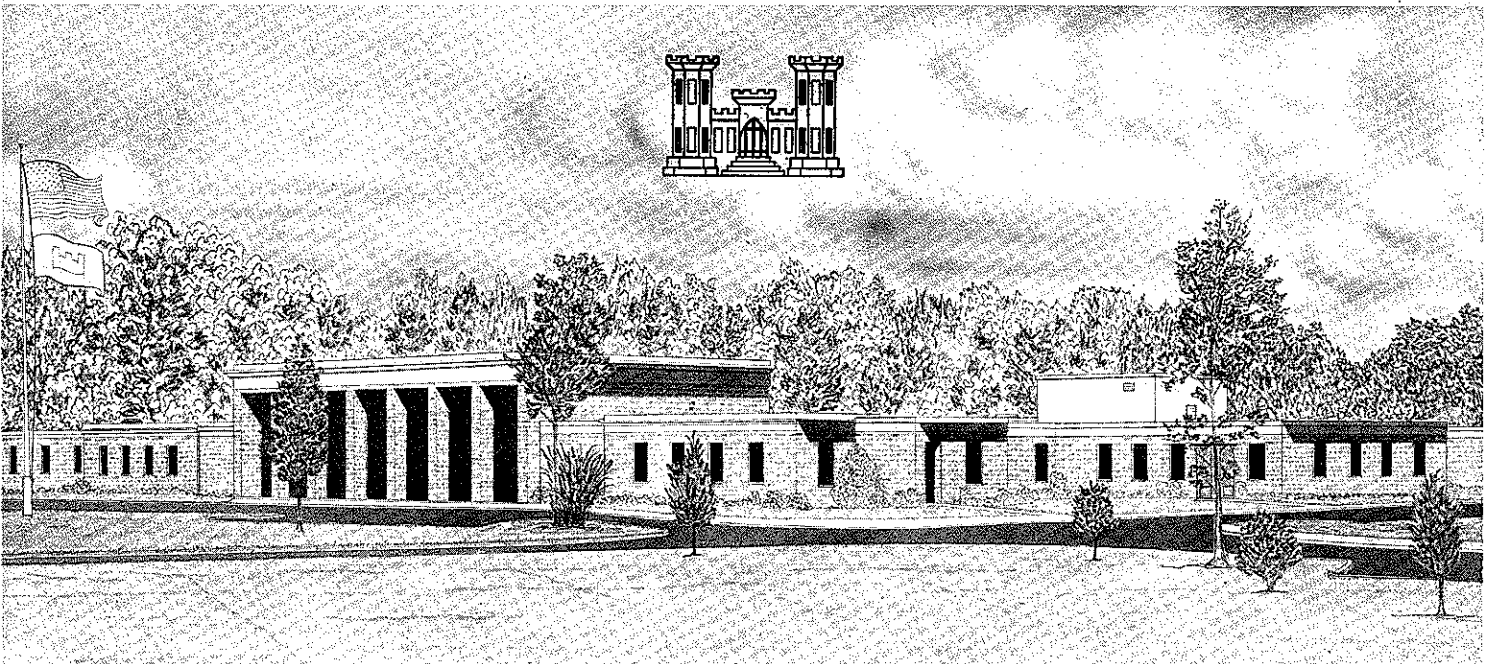TECHNICAL REPORT H-71-4

SELECTIVE WITHDRAWAL CHARACTERISTICS OF WEIRS

Hydraulic Laboratory Investigation

by

J. L. Grace, Jr.

June 1971

Sponsored by Office, Chief of Engineers, U. S. Army and

Assistant Secretary of the Army (R&D), Department of the Army

Conducted by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

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ARMY-MRC VICKSBURG, MISS.

FOREWORD

The experimental investigation reported herein was approved by the Director of the U. S. Army Engineer Waterways Experiment Station on 29 July 1969 as an In-House Laboratory Initiated Research Project (DA Project No. 4A061101A91D). In order to expedite the program, additional financial support was authorized by the Office, Chief of Engineers, on 23 December 1969. The studies were conducted in the Hydraulics Division of the Waterways Experiment Station during the period December 1969 to December 1970 under the direction of Mr. E. P. Fortson, Jr., Chief of the Hydraulics Division, and Mr. T. E. Murphy, Chief of the Structures Branch. The tests were conducted by Mr. J. P. Bohan under the supervision of Mr. J. L. Grace, Jr., Chief of the Spillways and Conduits Section. This report was prepared by Mr. Grace.

Mr. S. B. Powell of the Office, Chief of Engineers, observed experiments and reviewed results during conduct of the investigation.

COL Levi A. Brown, CE, and COL Ernest D. Peixotto, CE, were Directors of the Waterways Experiment Station during the conduct of the investigation and the preparation and publication of this report. Mr. F. R. Brown was Technical Director.

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CONTENTS

NOTATION

A Cross-sectional area of the zone of withdrawal, sq ft

b Width of the lake at the cross section of interest, ft

C_D Free flow discharge coefficient of weir

g Acceleration due to gravity, ft/sec^2

H Distance from the lower limit to the upper limit of the zone of withdrawal, ft

H_w Head on weir or depth of flow over weir, ft

p Exponent that is a function of C_D

Q Total discharge, cfs

t Time, sec

v_1 Local velocity at y_1, fps

v_2 Local velocity at y_2, fps

V Maximum velocity in the zone of withdrawal, fps

$\bar{V}$ Average velocity in the zone of withdrawal, fps

V_w Average velocity over the weir, fps

y_1 Vertical distance from the maximum velocity V to the corresponding local velocity v_1, ft

y_2 Vertical distance from the maximum velocity V to the corresponding local velocity v_2, ft

Y_1 Vertical distance from the maximum velocity to the lower limit of the zone of withdrawal, ft

Y_2 Vertical distance from the maximum velocity to the upper limit of the zone of withdrawal, ft

Z_o Vertical distance from weir crest to the lower limit of the zone of withdrawal, ft

$\Delta\rho_o$ Density difference of fluid between the elevations of the weir crest and the lower limit of the zone of withdrawal, g/cc

$\Delta\rho_1$ Density difference of fluid between the elevations of the maximum velocity and the corresponding local velocity v_1, g/cc

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$\Delta\rho_2$ Density difference of fluid between the elevations of the maximum velocity and the corresponding local velocity v_2 , g/cc

$\Delta\rho_{1m}$ Density difference of fluid between the elevations of the maximum velocity and the lower limit of the zone of withdrawal, g/cc

$\Delta\rho_{2m}$ Density difference of fluid between the elevations of the maximum velocity and the upper limit of the zone of withdrawal, g/cc

ρ_w Density of fluid at the elevation of the weir crest, g/cc

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
square feet	0.092903	square meters
feet per second	0.3048	meters per second
cubic feet per second	0.02831685	cubic meters per second
feet per second per second	0.3048	meters per second per second

SUMMARY

During 1969, the Corps of Engineers initiated laboratory research at the U. S. Army Engineer Waterways Experiment Station to determine the characteristics of withdrawal zones resulting from release of flows from randomly stratified lakes over weirs for developing means of predicting and controlling the quality of water discharged through downstream, fixed-level regulating structures. Stratification was generated in experimental facilities by means of differentials in both temperature and dissolved salt. Density distributions were determined from temperatures and salinities measured with thermistors and conductivity probes. Velocity distributions were obtained by dropping dye particles into the flow and photographing the resulting streaks with movie cameras.

Generalized expressions describing the limits of the zone of withdrawal and distribution of velocities therein were developed from analyses of the velocity and density distribution data. Means for evaluating those conditions where the free surface and/or bottom boundary dictates the upper and/or lower limits of the withdrawal zones were also determined. With the capability of predicting the velocity distribution to be anticipated for any given density distribution upstream of a weir, the weighted average technique can be applied to predict the value of any water-quality parameter of the outflow for which a profile in the lake is known.

SELECTIVE WITHDRAWAL CHARACTERISTICS OF WEIRS

Hydraulic Laboratory Investigation

PART I: INTRODUCTION

1. Effective planning, design, management, and operation of one or
more man-made lakes for optimum conservation and utilization of regional
water and related resources for many purposes involve, among others, the
problems of predicting, monitoring, and controlling the thermal and chemi-
cal quality of impounded waters and releases through spillways, power-
houses, and outlet works. Evaluation of the effectiveness of various struc-
tures in selectively withdrawing releases from various levels of stratified
man-made lakes is urgently needed relative to multipurpose projects in
which specific thermal and chemical requirements of the releases are de-
sired, based on existing and future needs. The desire to release quality
water requires monitoring the characteristics of water within lakes and
knowledge of the flow pattern to be expected in the immediate and upstream
vicinity of various regulating structures. Therefore, determination of the
effect on withdrawal of the size, shape, and spacing of multilevel openings
is desired to permit prediction and control of the stratum of the lake from
which releases are made and selection of effective locations for fixed
monitoring stations. Evaluation of the effectiveness of submerged skimming
weirs and walls or thermal barriers in preventing the intrusion of either
cold or warm water into powerhouse intakes and single-level outlet works
also is of primary concern.

2. The Corps of Engineers initiated laboratory research at the U. S.
Army Engineer Waterways Experiment Station (WES) to determine the charac-
teristics of withdrawal zones resulting from release of flows through ori-
fices (during 1966) and over weirs (during 1969) from randomly stratified
lakes for developing means of predicting and controlling the quality of
water discharged through various regulating structures. It was considered
that any practical method for predicting the quality of water discharged
through an inlet should be based upon the extent of the zone of withdrawal

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and the distribution of velocities within this zone. Then, if the distribution of one or more water-quality parameters is known, the resulting value of temperature, dissolved oxygen, or other parameter of the release could be computed by a weighted average technique. The results of investigations to determine the selective withdrawal characteristics of orifices are presented in reference 1 and the practicality of this technique has been verified by Clay and Fruh.[2,3] The facilities, experiments, test results, and data analyses utilized for determining generalized equations that describe the selective withdrawal characteristics of weirs are the basis of this report and are described in subsequent sections.

PART II: EXPERIMENTAL FACILITIES

3. The experimental facilities (fig. 1) contained a sharp-crested
weir of metal located in the center of a 1-ft*-wide, 2-ft-deep channel. A
headbay 40 ft long, 16 ft wide, and 4 ft deep was provided upstream of the
channel for the purpose of providing a relatively large supply of salt
water. Stratification was generated by means of differentials in both
temperature and dissolved salt. Fresh water was supplied by a pipe and
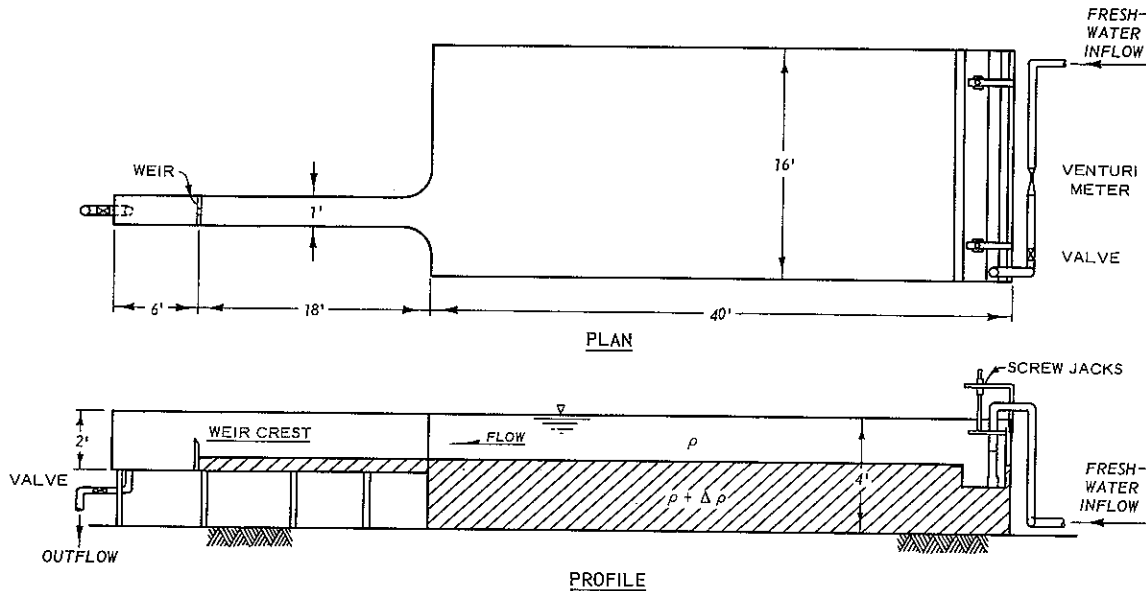

Fig. 1.   Experimental facilities

weir box that extended across the full width of the headbay. The weir
box was supported by screw jacks in order that the base or lip of the
box could be set at the desired interface or surface of the saline
water. The lower, denser stratum was generated by filling the headbay
and channel to a predetermined level with fresh water and mixing in
salt and dye to give the desired density and red color. The weir box
was placed at the surface of the saline water and fresh water was
slowly introduced through the box and over the broad-crested weir and

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* A table of factors for converting British units of measurement to metric
   units is presented on page ix.

saline water in order to establish the upper stratum. A drain pipe and valve were provided at the downstream end of the facilities for control of head differential and depth of flow over the weir. A venturi meter was used to measure the rate of freshwater inflow. The valve in the drain pipe was adjusted to release an equivalent rate of outflow measured by means of a V-notch weir.

4. Density distributions were determined from temperatures and salinities measured in place by means of commercially available thermistors, conductivity probes, and indicators (fig. 2). The actual density of the
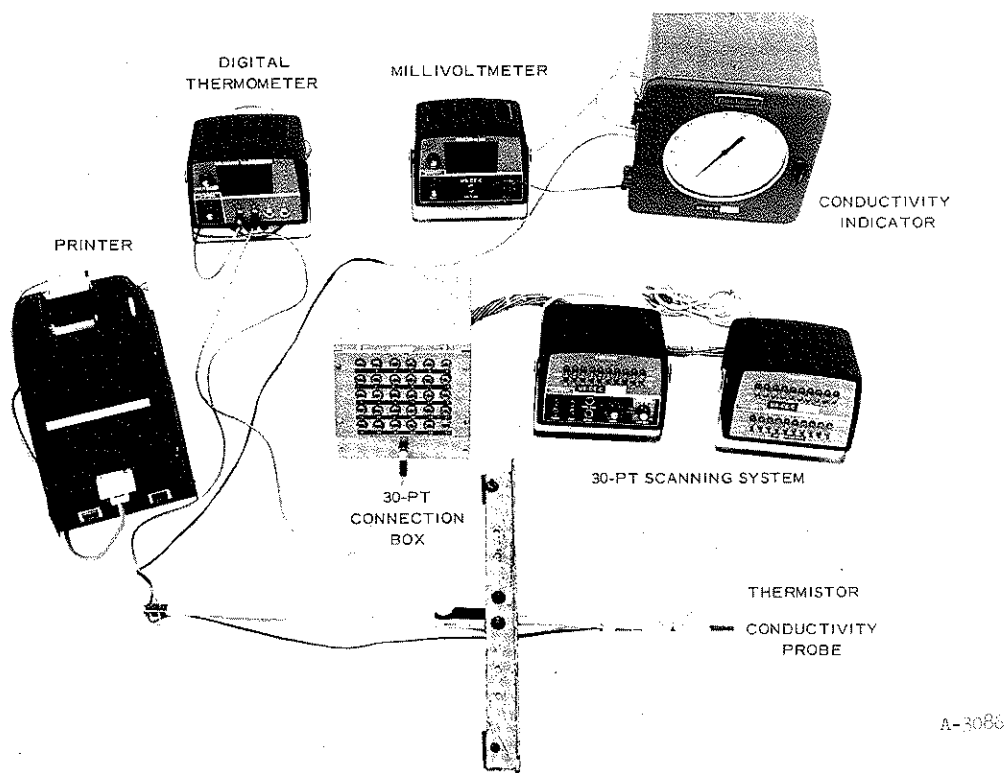
Fig. 2. Instrumentation used in experimental facilities

fresh and saline waters used in the facilities and for calibration purposes was determined by means of a gravimetric balance since the sump water was not distilled water. Initially, a very distinct two-layer stratification existed; however, the variable temperature of the atmosphere generally heated and cooled the upper stratum during the day and night to the extent that it was necessary to observe temperatures as well as salinity in order to determine an accurate measure of the density gradient in the

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experimental facilities. Velocity distributions were obtained by dropping
dye particles into the flow and photographing the resulting streaks with
movie cameras.

PART III: TESTS AND RESULTS

Test Procedure

5. After a two-layer stratification had been generated, the test was
initiated by introducing a given discharge of fresh water into the headbay
and releasing an equal amount over the weir and through the control valve
and drain. All of the tests were conducted with steady, uniform flow con-
ditions. Approximately 1 hr was required for the internal waves and sec-
ondary currents induced by initiating and/or changing the flow to settle
out or become steady and uniform. Velocity distributions were obtained by
dropping dye particles into the flume at three locations (1, 3, and 8 ft
upstream of the weir) and photographing the resulting streaks at each loca-
tion with movie cameras. Temperature and conductivity profiles were then
obtained at the locations. Temperatures of the water within the headbay
and of both the inflow and outflow were also observed. This procedure was
followed using several different sharp-crested weirs of various heights.

Basic Data

6. Movies of the dye streaks and grid system painted on the plastic
side of the channel were projected, stopping at the frame in which the streak
reached the bottom of the channel; the streak in this frame was traced and
used as the reference time t = 0 . The film was projected again and stopped
three other times so that the dye streaks could be traced. The error due to
distortion and refraction was taken into account at this point. A typical
set of traced dye streaks is shown in fig. 3. The time between the streaks
was determined based upon the known speed of the camera and the number of
frames between the traced streaks. The velocity at every 0.1 ft of depth
was calculated by dividing the scaled horizontal distance between the
traced streaks by the increment of time elapsed. Thus, three velocity dis-
tributions were obtained at each location upstream of the weir, and these
were averaged to yield one representative distribution.

7. Temperature and conductivity readings were converted to determine
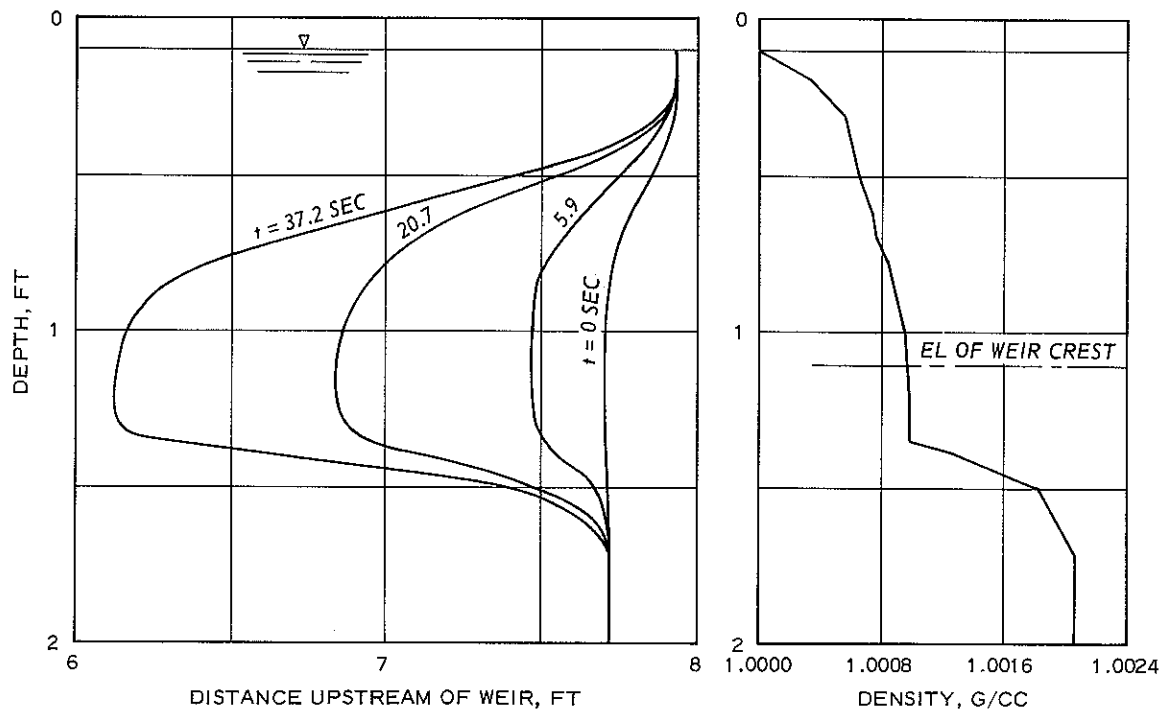
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Fig. 3. Typical traced dye streaks and density profile

densities at various depths, and these values were plotted to determine the
density profile at the locations 1, 3, and 8 ft upstream of the weir. A
comparison of the density and velocity distributions at the different loca-
tions upstream of the weir showed very close agreement. It appeared that
only those streaks within a distance of about three times the thickness of
the withdrawal zone upstream of the weir were distorted materially by con-
tractive effects. However, since the thickness of the zone of withdrawal
did tend to increase very slightly in an upstream direction, it was decided
that only the density and velocity distributions obtained at the location
8 ft upstream of the weir would be used in the data analyses. These dis-
tributions are presented in plates 1-4.

Data Analyses

8. Observations of stratified flow over the weir indicated that the
upper limit of the withdrawal zone always extended to the free surface, pro-
vided the vertical drain in the facilities downstream of the weir was not

permitted to control the vertical extent of withdrawal. The upper limit of the withdrawal zone over the weir could be restricted by releasing only relatively low rates of flow through the facilities with a relatively large depth of flow over the weir. Under similar conditions, the lower limit of withdrawal could be restricted by raising the drain outlet relative to the channel bottom and weir crest. Withdrawal characteristics of a vertical outlet are reported by Harleman, Morgan, and Purple.[4] Although the free surface determines the upper limit of the withdrawal zone upstream of a weir that controls flow, it was necessary to describe the lower limit of this zone of withdrawal. The important variables appeared to be the velocity over the weir, the density profile, and the vertical location of the weir relative to the free surface and the density profile. A definition sketch of the variables used in the analyses of data is presented in fig. 4. The data were plotted as shown in plate 5 in terms of a densimetric Froude number and the ratio of the thickness of the withdrawal zone to the head or depth of flow on the weir. The equation of the line shown is

$$V_w = 0.32 \left(\frac{Z_o + H_w}{H_w} \right) \sqrt{ \frac{\Delta \rho_o}{\rho_w} g Z_o } \tag{1}$$

where

V_w = average velocity over the weir, fps

Z_o = vertical distance from weir crest to the lower limit of the zone of withdrawal, ft

H_w = head on weir or depth of flow over weir, ft

$\Delta \rho_o$ = density difference of fluid between the elevations of the weir crest and the lower limit of the zone of withdrawal, g/cc

ρ_w = density of fluid at the elevation of the weir crest, g/cc

g = acceleration due to gravity, ft/sec^2

The data of Harleman and Elder[5] for which not more than 1 percent of the total flow under a plane skimmer wall was withdrawn from the stratum above the interface of a stratified lake upstream of the wall are presented in plate 5 also, as well as an average of similar data obtained at WES with three-dimensional models of specific, proposed submerged weirs of both the vertical-faced, sharp-crested[6] and sloped-faced, broad-crested[7] types.

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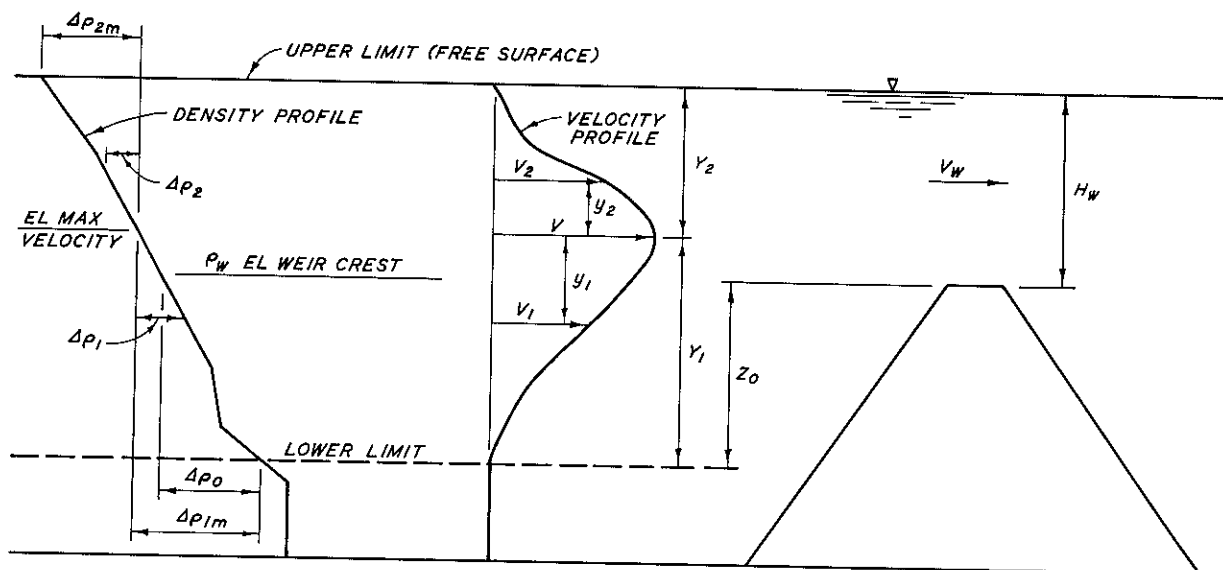
a. Submerged weir flow
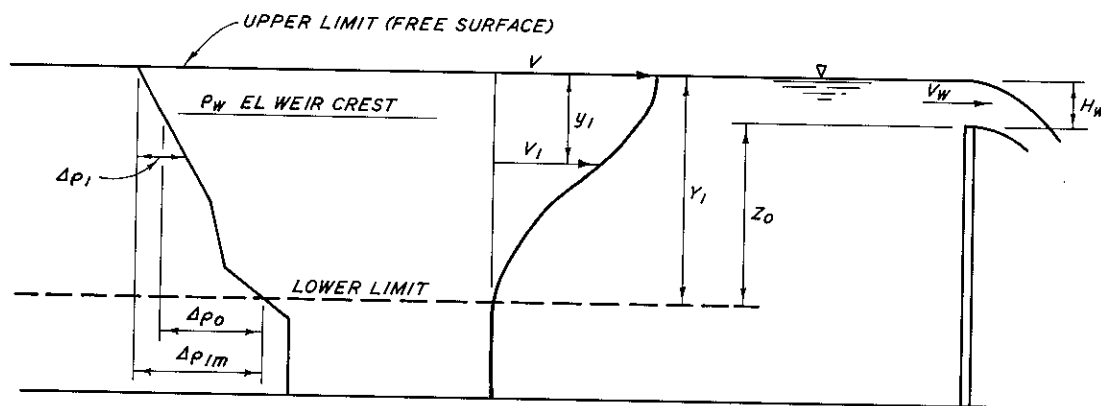
b. Free weir flow

Fig. 4. Definition sketch of variables

These data correlate well with the relations determined in the subject study through visual observations and physical measurement of the withdrawal zone and velocities.

9. The movies of the dye streaks indicated that in most cases with submerged weir flow, the maximum velocity within the zone of withdrawal occurred at elevations above and below that of the weir crest. With free weir flow, the maximum velocity for all practical purposes occurred at the free surface. A plot indicating the relative position of the maximum

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velocity to both the weir crest and the lower limit of withdrawal is presented in plate 6. The variables are defined as follows:

Y_1 = the distance from the elevation of maximum velocity to the lower limit of withdrawal, ft

Z_o = the distance from the elevation of the weir crest to the lower limit of withdrawal, ft

H_w = the head on the weir for free flow or the depth of flow over the weir for submerged flow, ft

Plate 6 can be used to determine where the maximum velocity will occur, after Z_o has been determined from equation 1.

10. Observations of the velocity and density distributions indicated that a reduction in velocity was always associated with a change in density. The most satisfactory fit of the experimental data with submerged weir flow was obtained by plotting $\frac{v_1}{V}$ and $\frac{v_2}{V}$ against $\frac{y_1 \Delta\rho_1}{Y_1 \Delta\rho_{1m}}$ and $\frac{y_2 \Delta\rho_2}{Y_2 \Delta\rho_{2m}}$, respectively, as shown in plates 7 and 8 where:

Y_1 = the vertical distance from the maximum velocity to the lower limit of the zone of withdrawal, ft

Y_2 = the vertical distance from the maximum velocity to the upper limit of the zone of withdrawal, ft

v_1 = the local velocity at y_1, fps

v_2 = the local velocity at y_2, fps

y_1 = vertical distance from the maximum velocity V to the corresponding local velocity v_1, ft

y_2 = vertical distance from the maximum velocity V to the corresponding local velocity v_2, ft

V = the maximum velocity in the zone of withdrawal, fps

$\Delta\rho_1$ = density difference of fluid between the elevations of the maximum velocity and the corresponding local velocity v_1, g/cc

$\Delta\rho_2$ = density difference of fluid between the elevations of the maximum velocity and the corresponding local velocity v_2, g/cc

$\Delta\rho_{1m}$ = density difference of fluid between the elevations of the maximum velocity and the lower limit of the zone of withdrawal, g/cc

$\Delta\rho_{2m}$ = density difference of fluid between the elevations of the maximum velocity and the upper limit of the zone of withdrawal, g/cc

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The equation describing the dimensionless velocity distribution for the portion below maximum velocity with submerged weir flow is

$$\frac{v_1}{V} = \left(1 - \frac{y_1 \Delta \rho_1}{Y_1 \Delta \rho_{1m}}\right)^3 \qquad (2)$$

This is of the same form as that observed with the orifice and negligible boundary effects.[1]

11. The dimensionless velocity distribution for the portion above maximum velocity with submerged weir flow is

$$\frac{v_2}{V} = 1 - \left(\frac{y_2 \Delta \rho_2}{Y_2 \Delta \rho_{2m}}\right)^2 \qquad (3)$$

This is of the same form as that observed with the submerged orifice and the restricting free surface boundary effect.[1]

12. With free weir flow, the maximum velocity occurred at the water surface and the dimensionless velocity distributions observed were described by an equation of the form that satisfactorily described the distributions observed with either submerged orifice[1] or submerged weir flow and the restricting free surface boundary effect (see plates 9 and 10). However, different relations were required to satisfy the different velocity distributions observed and as affected by a different value of the weir discharge coefficient with free flow conditions, C_D . The following general equation describes the dimensionless velocity distributions observed with free weir flow and the free surface boundary effect:

$$\frac{v_1}{V} = 1 - \left(\frac{y_1 \Delta \rho_1}{Y_1 \Delta \rho_{1m}}\right)^p \qquad (4)$$

where p is an exponent that is a function of the free flow discharge coefficient of the weir. Based on the available data, it appears that p values of 3/2, 1/2, and 1/5 are indicated for C_D values of 3.00, 3.33, and 4.10, respectively.

13. Since the magnitude of velocities at a given elevation appeared to be the same except in the immediate vicinity of the side boundaries, it was assumed that the vertical distribution of velocities is constant

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throughout the full width of a stratified lake. Based upon this assumption, the relation between average velocity $\overline{V}$ and the maximum velocity V in the zone of withdrawal and across any cross section of a stratified lake is expressed as follows:

$$\frac{\overline{V}}{V} = \frac{Q}{AV} = \frac{b\displaystyle\int_0^{Y_1} v_1 \, dy_1 + b\displaystyle\int_0^{Y_2} v_2 \, dy_2}{bHV} \tag{5}$$

where

   $\overline{V}$ = average velocity in the zone of withdrawal, fps

   Q = total discharge, cfs

   A = cross-sectional area of the zone of withdrawal, sq ft

   b = width of the lake at the cross section of interest, ft

   H = distance from the lower limit to the upper limit of the zone of withdrawal, ft

This can be written as

$$\frac{\overline{V}}{V} = \frac{1}{H}\left(\int_0^{Y_1} \frac{v_1}{V} \, dy_1 + \int_0^{Y_2} \frac{v_2}{V} \, dy_2 \right) \tag{6}$$

The appropriate relations between the local and maximum velocities for submerged or free weir flow conditions (equations 2 and 3 or 4, respectively) can be substituted into equation 6 and the resulting integrals can be solved when $\frac{\Delta\rho}{\Delta\rho_m}$ is expressed as a function of $\frac{y}{Y}$. If the density profile in the lake is known, this can be easily accomplished. The ratio $\frac{\Delta\rho}{\Delta\rho_m}$ may be several different functions of $\frac{y}{Y}$ in the zone of withdrawal depending upon the density profile; thus, a separate integral must be written for each $\frac{\Delta\rho}{\Delta\rho_m} = f\left(\frac{y}{Y}\right)$. Each of these integrals can now be evaluated and all added together. Letting the sum of the integrals equal K, the equation can be written as follows:

$$\frac{\overline{V}}{V} = \frac{K}{H} \tag{7}$$

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where $\overline{V} = Q/bH$. Then

$$\frac{Q}{bH\overline{V}} = \frac{K}{H} \tag{8}$$

yielding

$$V = \frac{Q}{b\overline{K}} \tag{9}$$

It is now possible to determine the upper and lower limits of the zone of withdrawal and the velocity distribution therein. With the capability of predicting the velocity distribution to be anticipated for any given density distribution upstream of a weir, the weighted average technique can be applied to predict the value of any water-quality parameter of the outflow for which a profile in the lake is known.

PART IV: DISCUSSION

14. Although the scope and results obtained in the current studies reported herein are not as comprehensive as desired, means of predicting the limits of and the velocity distribution within the zone of withdrawal upstream of a weir have been developed. From these, the relative contribution of selected vertical extents or each layer to the total release can be determined. Then, with assumed or known gradients of temperature, dissolved oxygen content, and/or other water-quality parameters, the value of each parameter representative of the total release can be estimated by means of weighted averages. If other pertinent hydrographic data and methodology are known, these results can be applied to predict the effectiveness of proposed selective withdrawal structures and plans of operation for the preservation and enhancement of water resources.

15. Three-dimensional models operated in such a manner that they reproduce typical hydrographic and even meteorological records should be utilized to investigate the effects of unsteady and varied flow conditions due to variations in geometry, inflows, outflows, storage, density, and the local environment that are characteristic of prototype man-made lakes. The results of even limited tests in such models would be most beneficial in the development of mathematical models and computer programs for solution of the problems associated with the planning, design, and management of man-made lakes.

16. Additional studies are desired to investigate model scale effects and the relative importance of viscous effects. These are believed to be most pertinent and are required for development of models and techniques that accurately simulate prototype systems. For example, it appears that similitude of stratified flow systems should be based upon the Froudian criteria, but surely the viscous effects and the Reynolds criteria should be considered so that the fundamental character of flow is the same in both model and prototype. This could be accomplished by reducing the width of the model to increase approach velocities and obtain values of Reynolds numbers comparable to those anticipated in the prototype. However, results of tests in 1:40- and 1:60-scale, undistorted, three-dimensional

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models of proposed skimmer weirs agree most favorably with those obtained for the small and generalized study reported herein.

17. Stratified flow patterns observed in the 1:40-scale, three-dimensional model of the outlet works proposed for Meramec Park Reservoir, which reproduced approximately 400 to 500 ft of the reservoir topography and a curved, narrow approach channel upstream of a single, low-level intake, indicated local geometry to be of importance also. The narrow approach channel and shallow depth of the reservoir created shear along the interface that during high flows caused considerable mixing along the interface. Considerably greater mixing and/or blending of the warm and cold waters would be anticipated with an intake structure located in a relatively shallow, narrow section of a man-made lake. The interface tends to be elevated and lowered, respectively, along the inner and outer portions of a curved approach channel. Based upon these observations, the geometry adjacent to intakes may have a significant effect upon the withdrawal characteristics.

18. It is considered that the use of hydraulic models to evaluate the effectiveness of specific proposed structures should be encouraged to ensure reasonably adequate and accurate performance of proposed projects as well as gain additional knowledge concerning the mechanics of stratified flow and refinement of the state-of-the-art.

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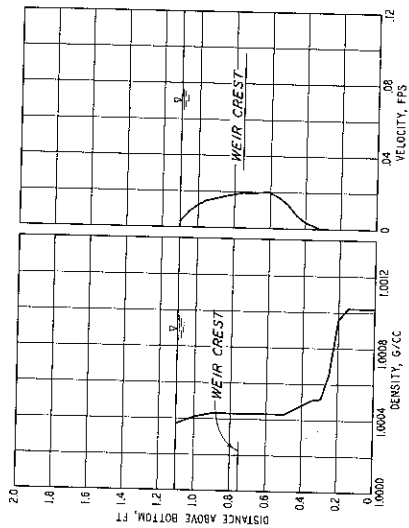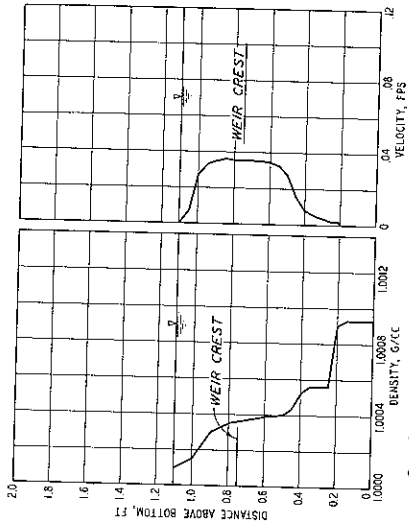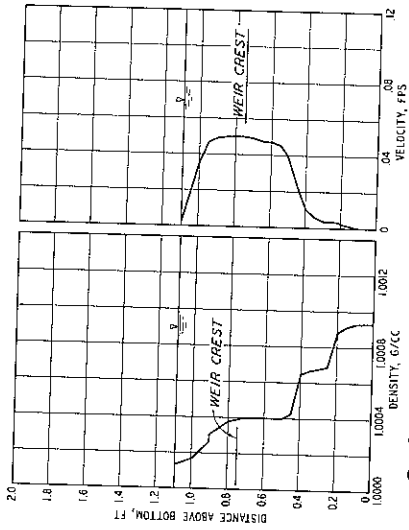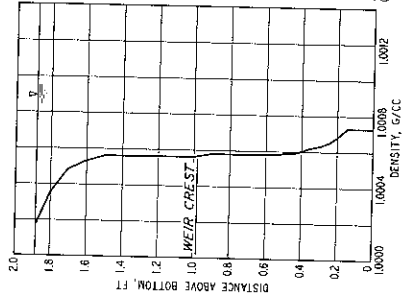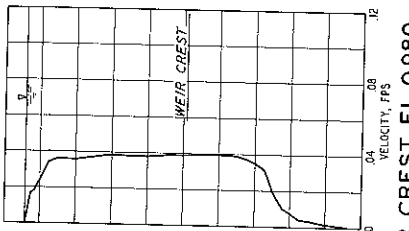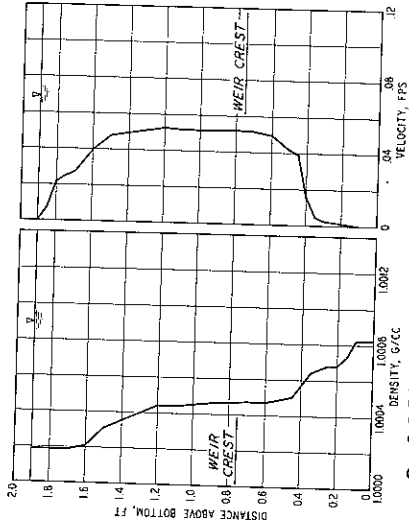
VERTICAL DISTRIBUTION OF
DENSITY AND VELOCITY

DISCHARGES 0.00646 TO 0.0516 CFS
SUBMERGED WEIR CREST
ELEVATIONS 0.750 AND 0.980

PLATE I
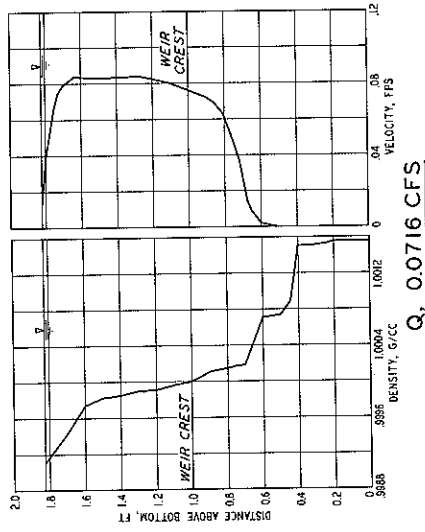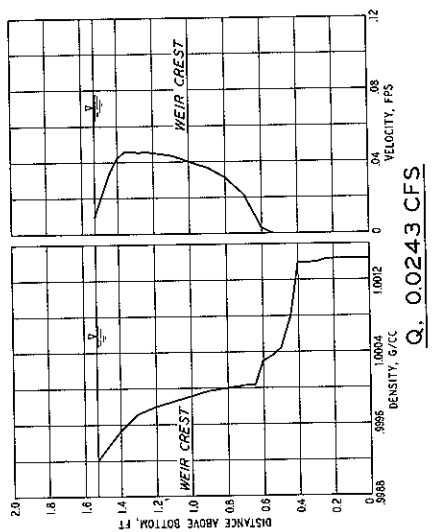
VERTICAL DISTRIBUTION OF
DENSITY AND VELOCITY
DISCHARGES 0.00897 TO 0.0716 CFS
SUBMERGED WEIR CREST
ELEVATION 1.000
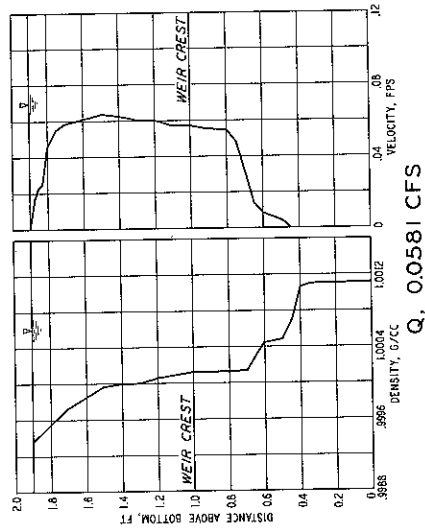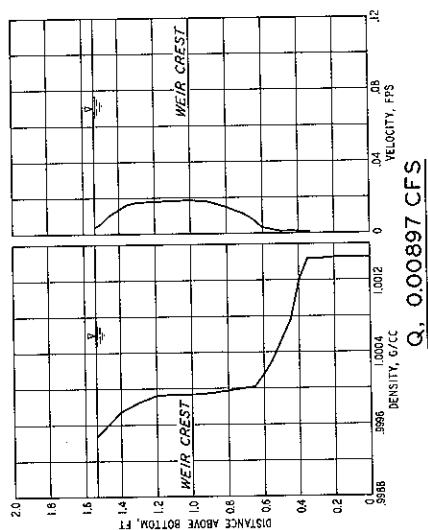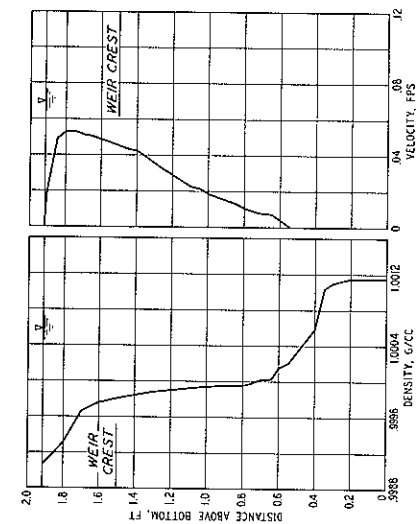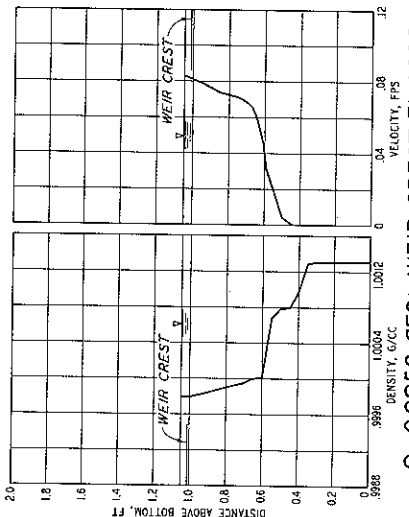
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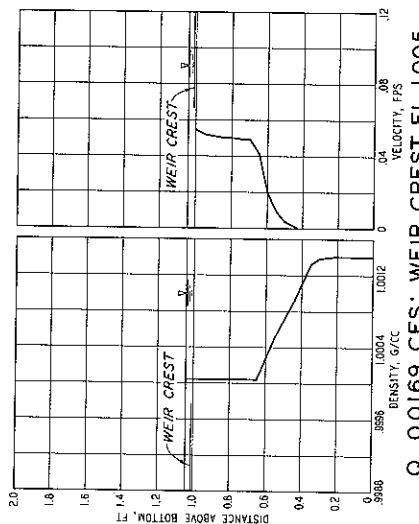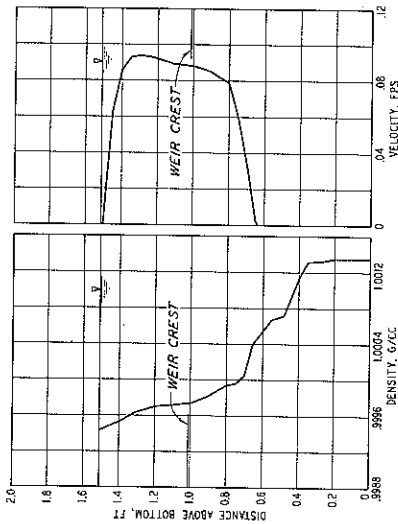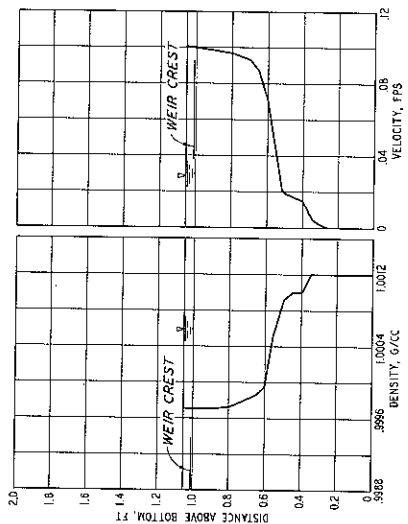
VERTICAL DISTRIBUTION OF
DENSITY AND VELOCITY
DISCHARGES 0.0169 TO 0.0577 CFS
WEIR CREST ELEVATIONS
1.005 AND 1.500

PLATE 3
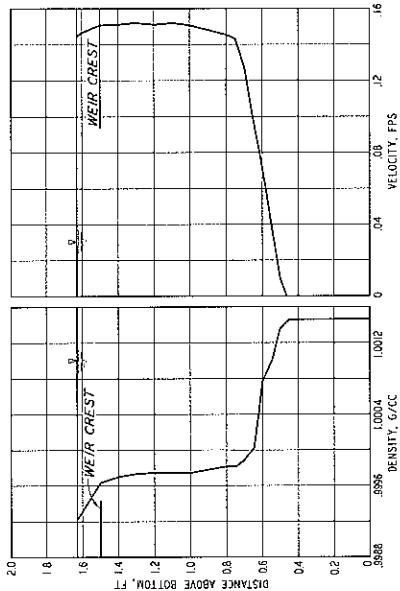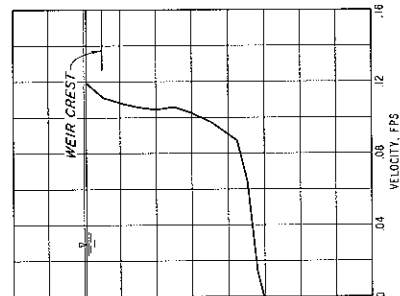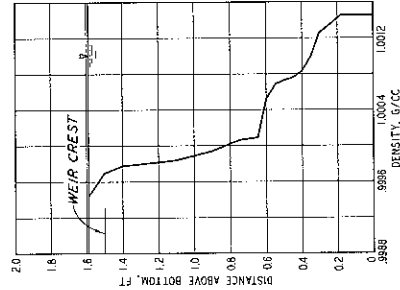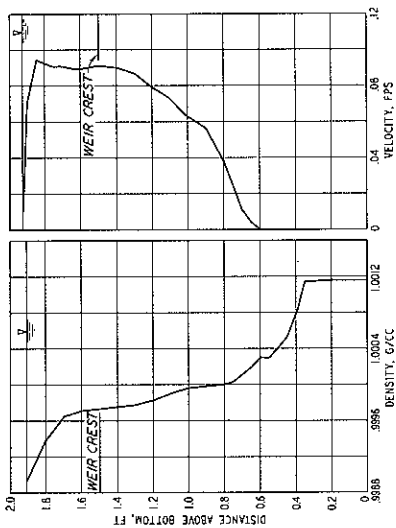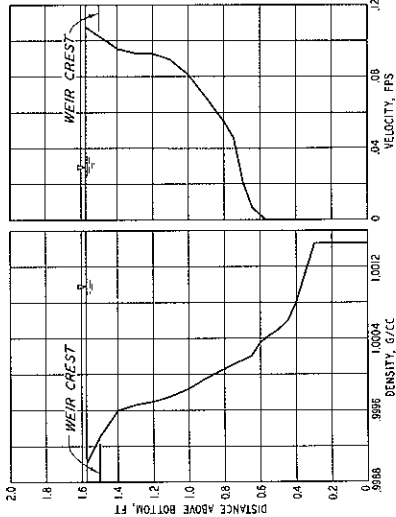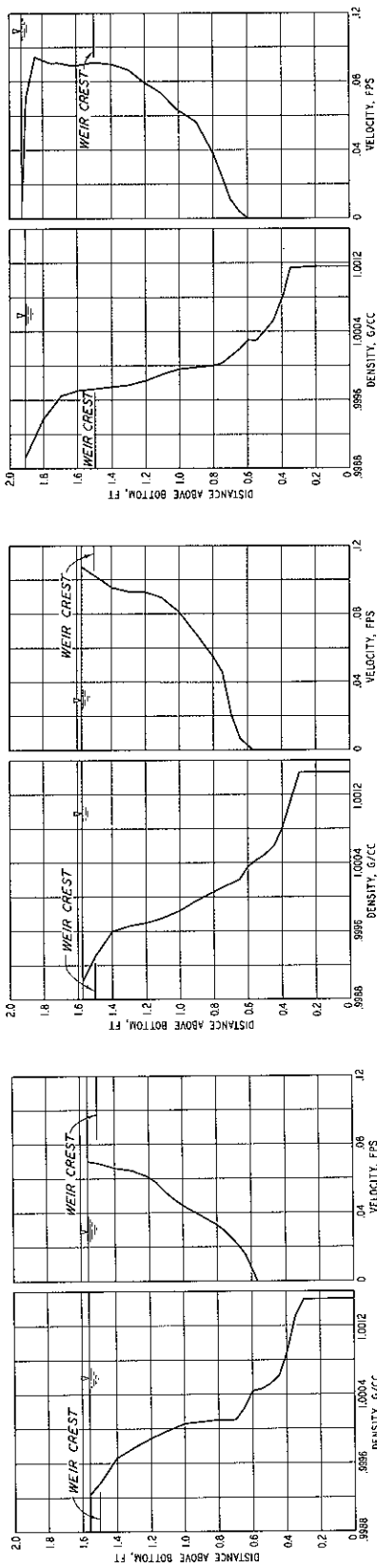
VERTICAL DISTRIBUTION OF
DENSITY AND VELOCITY
DISCHARGES 0.0334 TO 0.1360 CFS
WEIR CREST ELEVATION 1.500

PLATE 4

$$\frac{V_w}{\sqrt{\frac{\Delta \rho_o}{\rho_w} g z_o}} = 0.32 \left(\frac{z_o + H_w}{H_w} \right)$$

LEGEND

○   WES GENERAL INVESTIGATION

△   HARLEMAN AND ELDER (1% DRAWDOWN)

— — WES SPECIFIC PROJECT MODELS
(WEST POINT, MERAMEC PARK,
CLARENCE CANNON)

y-axis: $\dfrac{V_w}{\sqrt{\dfrac{\Delta \rho_o}{\rho_w} g z_o}}$

x-axis: $\dfrac{z_o + H_w}{H_w}$

WITHDRAWAL
CHARACTERISTICS OF WEIRS

PLATE 5

$$\frac{Y_1}{H_w + Z_o} = \left[\text{SIN} \left(1.57 \frac{Z_o}{H_w + Z_o} \right) \right]^2$$
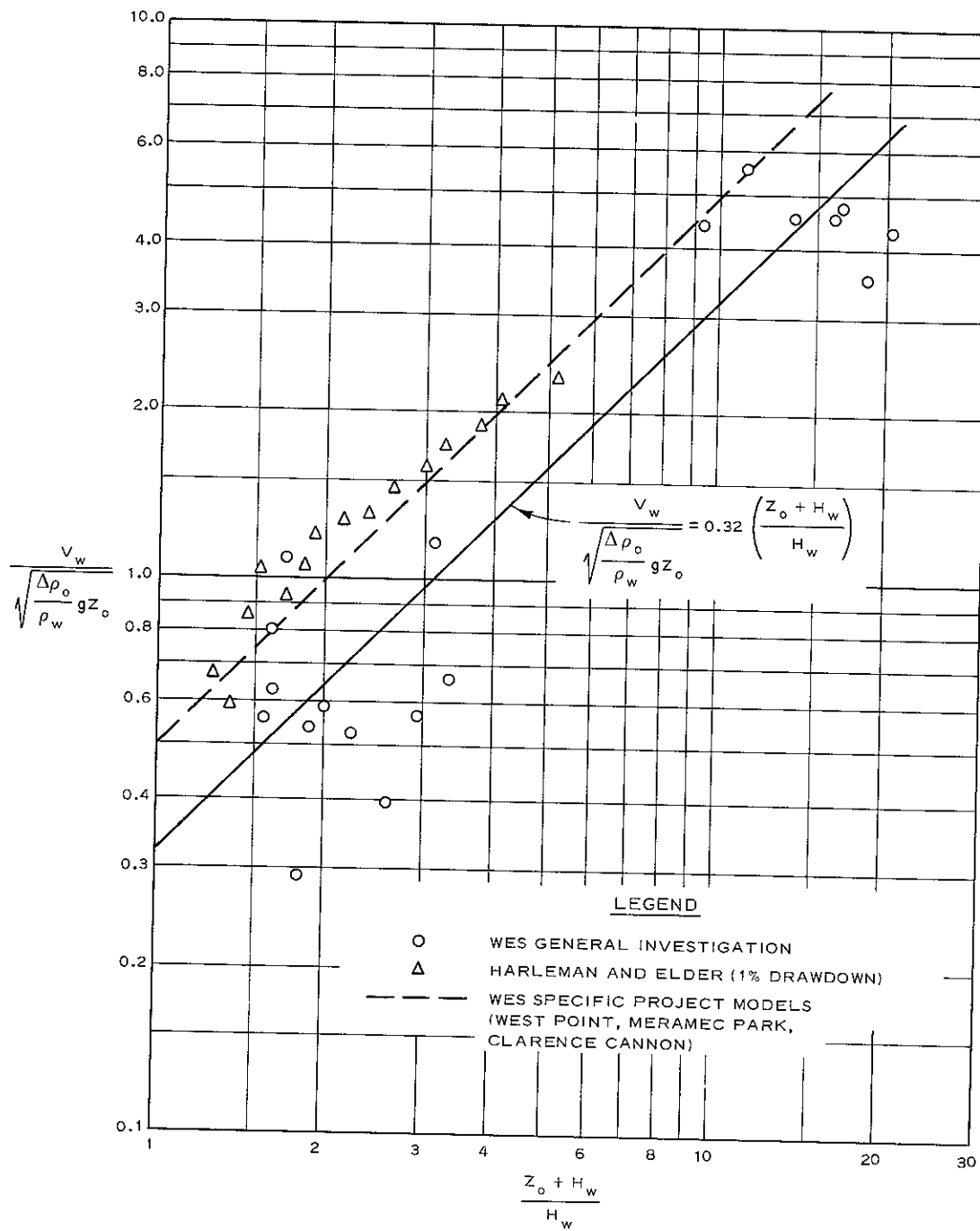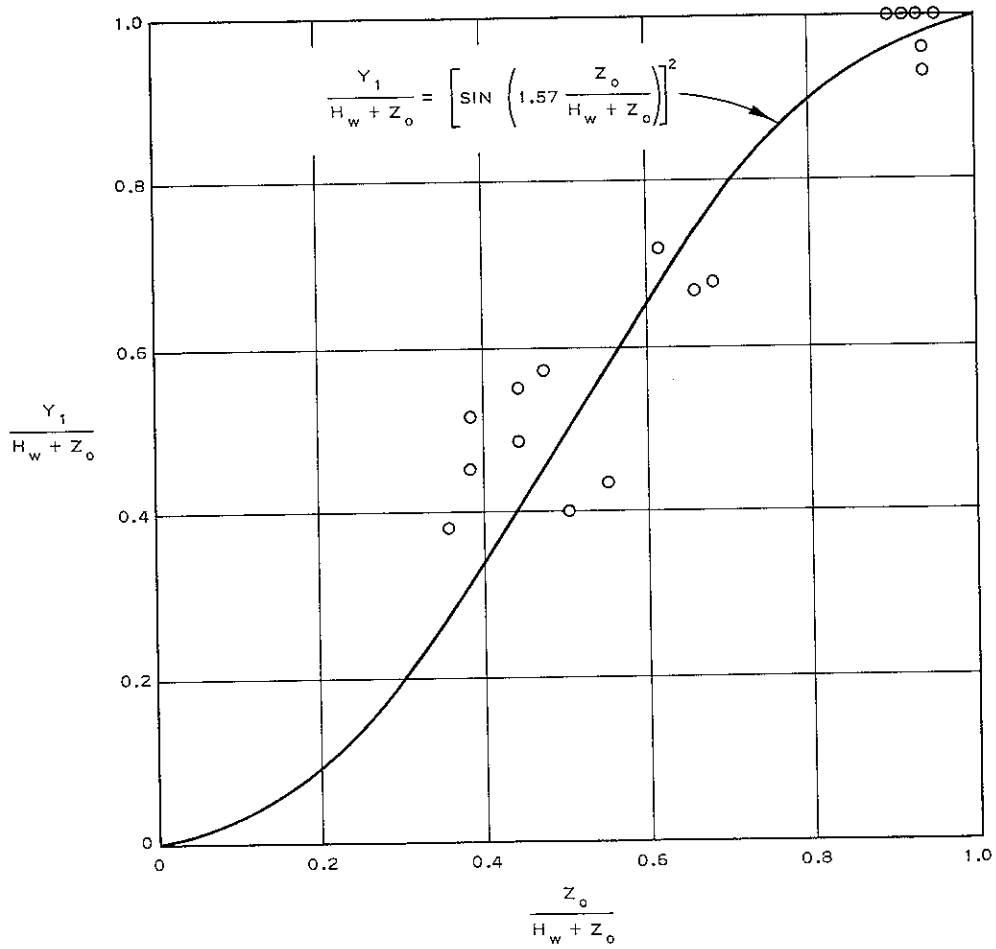
RELATIVE POSITION OF
MAXIMUM VELOCITY AND WEIR CREST

PLATE 6

The figure plots the dimensionless velocity ratio $\dfrac{v_1}{V}$ (vertical axis, from 0 to 1.0) against $\dfrac{y_1 \Delta \rho_1}{Y_1 \Delta \rho_{1m}}$ (horizontal axis, from 0 to 1.0), with data points and a fitted curve described by

$$\frac{v_1}{V} = \left(1 - \frac{y_1 \Delta \rho_1}{Y_1 \Delta \rho_{1m}}\right)^3$$
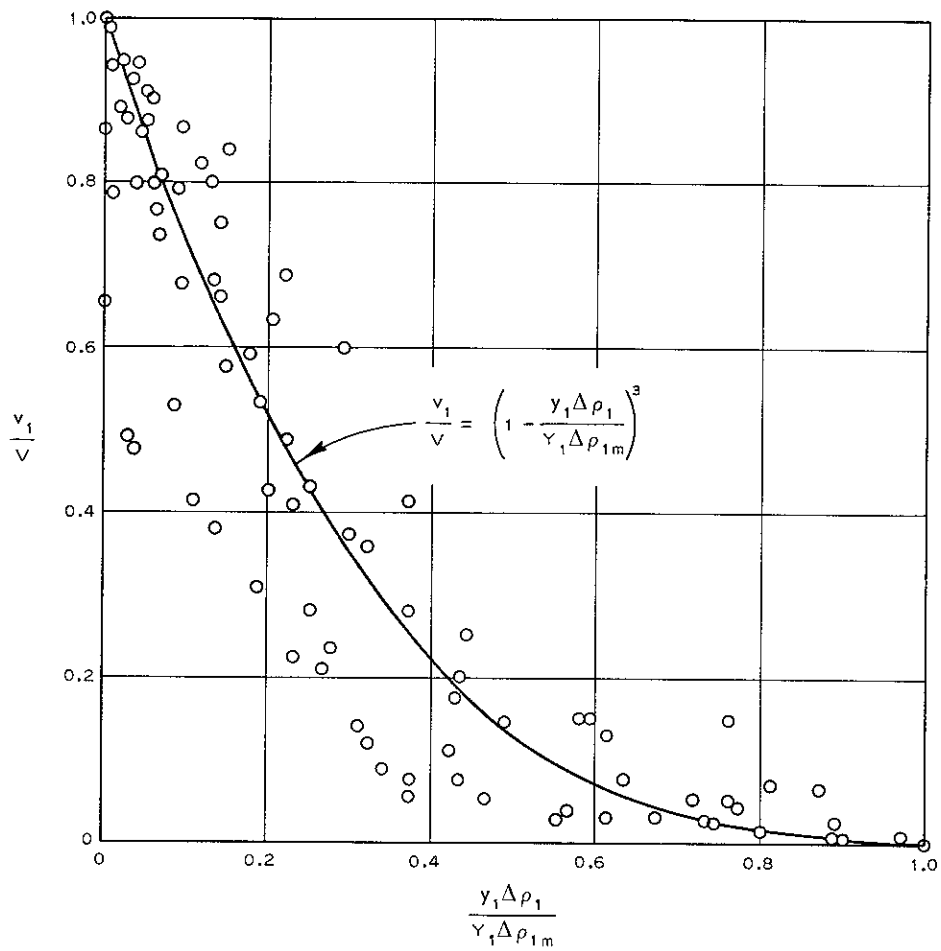
DIMENSIONLESS VELOCITY DISTRIBUTION
FOR PORTION BELOW MAXIMUM VELOCITY
WITH SUBMERGED WEIR FLOW
(BOUNDARY EFFECTS NEGLIGIBLE)

PLATE 7

$$\frac{v_2}{V} = 1 - \left(\frac{y_2 \Delta \rho_2}{Y_2 \Delta \rho_{2m}}\right)^2$$

$1 - \dfrac{v_2}{V}$

$\dfrac{y_2 \Delta \rho_2}{Y_2 \Delta \rho_{2m}}$
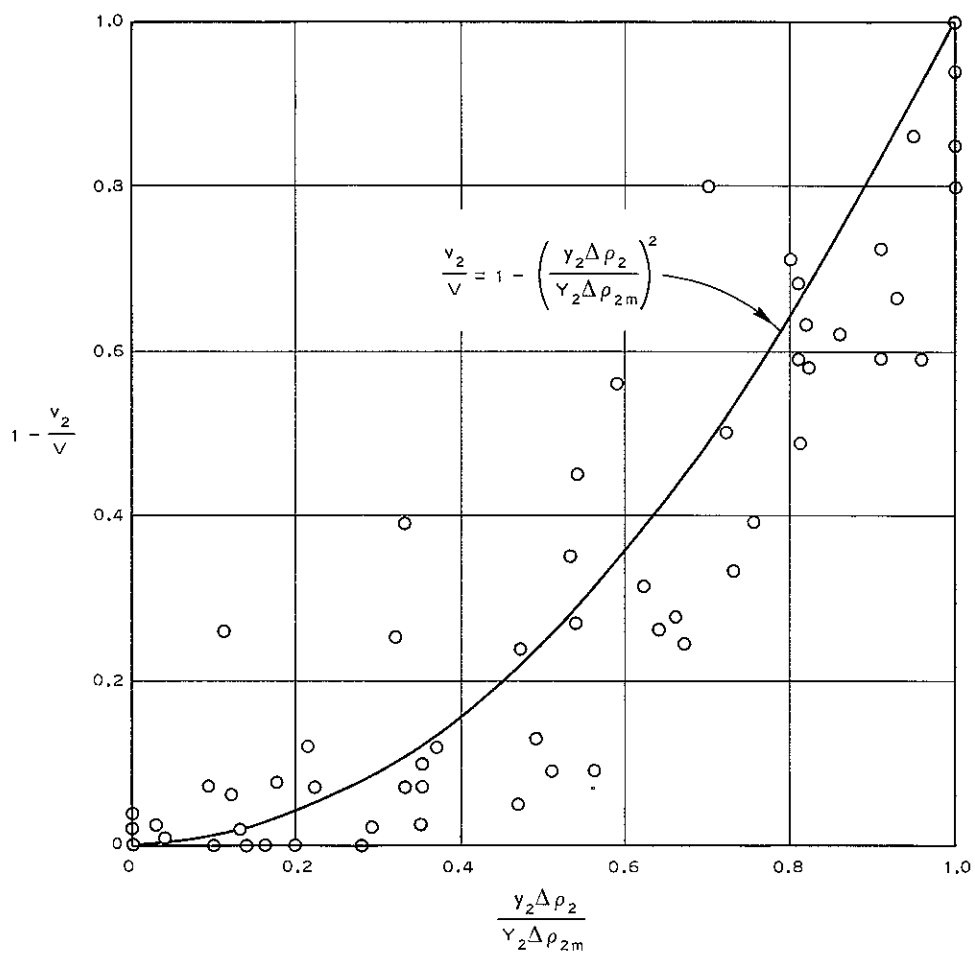
DIMENSIONLESS VELOCITY DISTRIBUTION
FOR PORTION ABOVE MAXIMUM VELOCITY
WITH SUBMERGED WEIR FLOW
(FREE SURFACE BOUNDARY EFFECT)
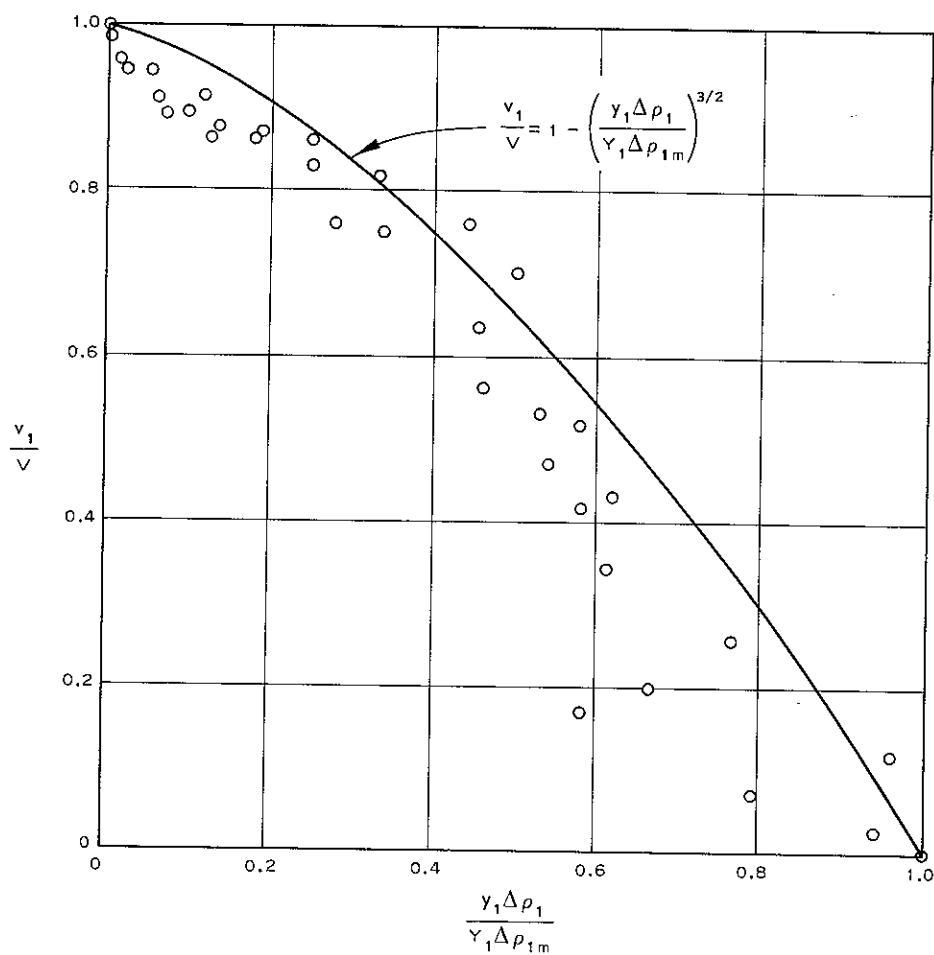
PLATE 8

$$\frac{v_1}{V} = 1 - \left(\frac{y_1 \Delta \rho_1}{Y_1 \Delta \rho_{1m}}\right)^{3/2}$$

DIMENSIONLESS VELOCITY DISTRIBUTION
FOR FREE WEIR FLOW (FREE SURFACE
BOUNDARY EFFECT), $C_D = 3.00$
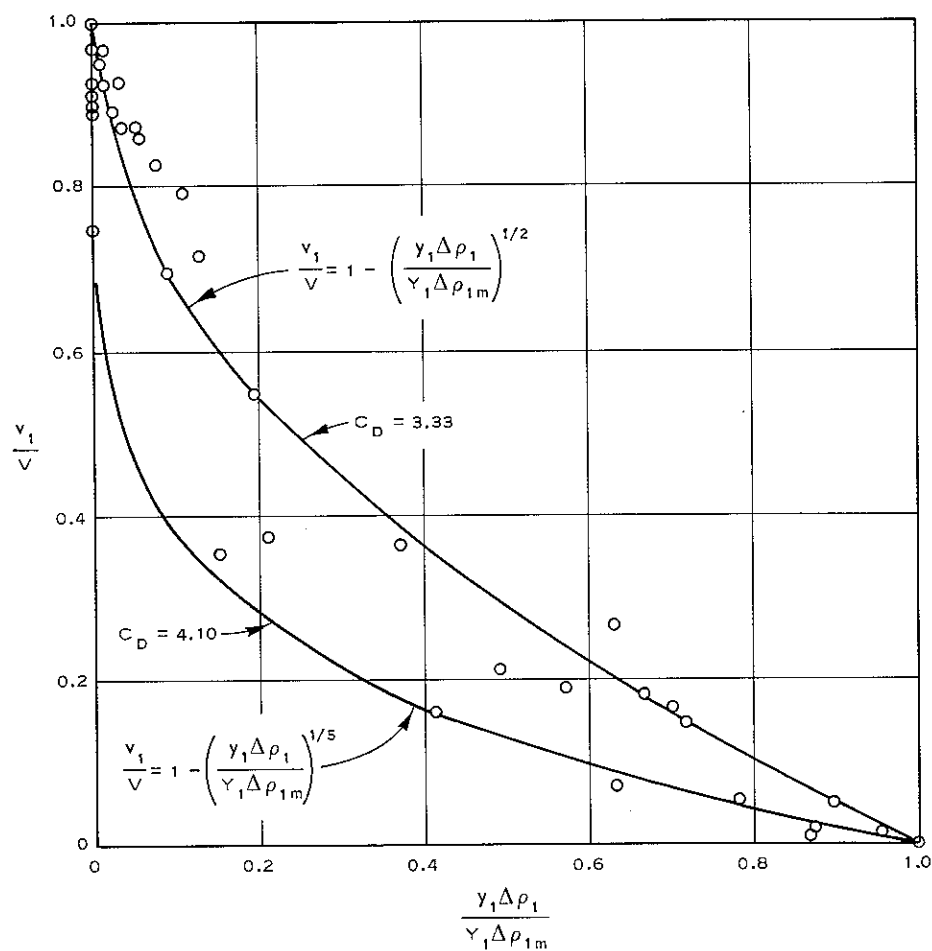
PLATE 9

DIMENSIONLESS VELOCITY DISTRIBUTION
FOR FREE WEIR FLOW (FREE SURFACE
BOUNDARY EFFECT), $C_D = 3.33$ AND 4.10

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13. ABSTRACT

During 1969, the Corps of Engineers initiated laboratory research at the U. S. Army Engineer Waterways Experiment Station to determine the characteristics of withdrawal zones resulting from release of flows from randomly stratified lakes over weirs for developing means of predicting and controlling the quality of water discharged through downstream, fixed-level regulating structures. Stratification was generated in experimental facilities by means of differentials in both temperature and dissolved salt concentration. Density distributions were determined from temperatures and salinities measured with thermistors and conductivity probes. Velocity distributions were obtained by dropping dye particles into the flow and photographing the resulting streaks with movie cameras. Generalized expressions describing the limits of the zone of withdrawal and distribution of velocities therein were developed from analyses of the velocity and density distribution data. Means for evaluating those conditions where the free surface and/or bottom boundary dictates the upper and/or lower limits of the withdrawal zones were also determined. With the capability of predicting the velocity distribution to be anticipated for any given density distribution upstream of a weir, the weighted average technique can be applied to predict the value of any water-quality parameter of the outflow for which a profile in the lake is known.

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Stratified flow						
Weirs						